

# ANALYTICAL STUDY ON HIGH STRENGTH CONCRETE SHEAR WALLS

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**Abstract.** *This paper presents an analytical study on the behavior of high strength concrete (HSC) shear walls. Several experiments on HSC shear walls with concrete strength above 60 MPa have been selected to be studied. Data from various experiments were collected and nominal wall strengths have been calculated using several building code formulas, such as those of the ACI (American), AIJ (Japanese), and EC (Eurocode). Subsequently, nominal wall strengths from the building code formulas were compared with actual wall strengths from experiments. Moreover, normalized actual wall strengths over nominal wall strengths and the average shear stresses were also plotted against some significant factors such as shear span ratio, axial load ratio, ratio of longitudinal and transverse reinforcements, etc., in order to observe the behavior of HSC shear walls as influenced by various parameters. The analysis results show that most of the building code formulas underestimate HSC wall strengths for low shear-span ratio (below 2.0) but they predict more accurately for high shear-span ratio (above 2.0). Furthermore, from the results, it seems that axial load up to  $0.15 (f'_c A_g)$  does not contribute much to the wall strengths. In addition, the comparative study shows that the contribution of longitudinal reinforcement to wall strengths is more significant than that of the transverse reinforcement. This phenomenon is not accounted for in most building code formulas. Thus, there is a need to develop an expression that can take into account this phenomenon and that can yield better predictions of the strength of HSC walls.*

## 1 INTRODUCTION

Nowadays, the use of high strength concrete as a structural material has become more common in engineering practice. Compared to normal strength concrete, high strength concrete has many advantages including higher stiffness, higher durability, lower permeability, lower porosity, etc. These advantages make high strength concrete able to cope with modern architectural and structural needs. One of the benefits of high strength concrete is the reduction in the size of structural members such as columns, walls, etc. which can provide more space for other purposes. Furthermore, high strength concrete with low permeability and low porosity can provide better protection for steel reinforcement when corrosion is a major issue. This is a very important aspect when durability of the structure is a concern.

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Shear walls have been used widely in many structures since they provide good resistance to lateral loadings. Moreover, not only for resisting lateral loadings, many structural walls are optimized to resist gravity loading as well. This study presents a review on the behavior of high strength concrete shear walls (HSC walls). Experiments on HSC walls reported by researchers from different countries<sup>1-6</sup> were collected and studied. Data from those experiments were used to calculate nominal wall strengths using building code formulas, such as those formulas recommended by the American Concrete Institute (ACI 318)<sup>7</sup>, Architectural Institute of Japan (AIJ)<sup>8</sup>, and Eurocode (EC 8)<sup>9</sup>. Subsequently, the nominal wall strengths calculated using the building code formulas were compared with actual wall strengths obtained from experiments. The predicted failure modes were also compared with the actual failure modes. In addition, to investigate further the behavior of HSC walls with various parameters, normalized actual wall strengths and normalized average shear stresses were plotted against shear span ratio, drift ratio, axial load ratio, longitudinal and transverse reinforcement ratios, and concrete strength. Finally, general conclusions based on this analytical study were made regarding the behavior of HSC walls which might be used as a basis for further experimental studies about HSC walls in the future.

## 2 HSC WALLS EXPERIMENTS

As mentioned before, several experiments about HSC walls reported by researchers from different countries<sup>1-6</sup> were collected and studied. These experiments were reported by Kabeyasawa and Hiraishi<sup>1</sup>, Gupta and Rangan<sup>2</sup>, Yun et al.<sup>3</sup>, Farvashany et al.<sup>4</sup>, Yan et al.<sup>5</sup>, and Deng et al.<sup>6</sup>. Data from these experiments were collected in terms of concrete strength ( $f'_c$ ), shear span ratio ( $H/L$ ; where  $H$  is the wall height and  $L$  is the wall length), axial load ratio ( $P/(f'_c A_g)$ ; where  $P$  is the axial load in wall, and  $A_g$  is the gross cross sectional area of wall), longitudinal and transverse reinforcement contributions ( $\rho_l f_{yl}$  and  $\rho_t f_{yt}$ ; where  $\rho_l$  and  $\rho_t$  are longitudinal and transverse reinforcement ratios of wall,  $f_{yl}$  and  $f_{yt}$  are the yield strengths of longitudinal and transverse reinforcements), maximum wall strength (lateral load) obtained from experiment, and drift ratio (%). These data are presented in Table 1.

## 3 ANALYTICAL STUDY

The nominal wall strengths were then calculated according to the methods of the ACI 318<sup>7</sup>, AIJ<sup>8</sup>, and EC 8<sup>9</sup>. The flexural strength of the walls was calculated based on flexural theory for members subjected to bending and axial loads whereas the shear strength was calculated using formulas given in the codes. The smaller value of the flexural strength and the shear strength was then taken as the nominal strength of the walls as well as the respective predicted failure mode. Shear strength formulas according to various building codes<sup>7-9</sup> are given as follows.

### 3.1 ACI 318 (Chapter 21)

$$V_n = A_{cv}(\alpha_c \lambda \sqrt{f'_c} + \rho_t f_{yt}) \quad (1)$$

where:

$V_n$  = nominal wall shear strength (N)

$A_{cv}$  = gross area of concrete section bounded by web thickness and length of section in the direction of shear force considered ( $\text{mm}^2$ )

$\alpha_c$  = coefficient defining the relative contribution of concrete strength to nominal wall shear strength, which may be taken as 0.25 for  $H/L \leq 1.5$ , 0.17 for  $H/L \geq 2.0$ , and varies linearly between 0.25 and 0.17 for  $H/L$  between 1.5 and 2.0

$\lambda$  = modification factor reflecting the reduced mechanical properties of lightweight concrete, all relative to normal weight concrete of the same compressive strength

| No. | Ref No [No] | Specimen ID | Concrete Strength ( $f'_c$ ) (MPa) | Shear Span Ratio (H/L) | Axial Load Ratio [ $P/(f'_c A_g)$ ] | Longitudinal Reinforcement Ratio ( $\rho_l f_y$ ) (MPa) | Transverse Reinforcement Ratio ( $\rho_t f_y$ ) (MPa) | $V_{max}$ (kN) | Drift (%) |
|-----|-------------|-------------|------------------------------------|------------------------|-------------------------------------|---|---|----------------|-----------|
| 1   | [1]         | NW-1        | 87.6                               | 2.00                   | 0.11                                | 5.34  | 5.34  | 1062           | 1.970     |
| 2   | [1]         | NW-2        | 93.6                               | 1.33                   | 0.10                                | 5.34  | 5.34  | 1468           | 1.490     |
| 3   | [1]         | NW-3        | 55.5                               | 2.00                   | 0.13                                | 2.01  | 2.01  | 717            | 0.990     |
| 4   | [1]         | NW-4        | 54.6                               | 2.00                   | 0.16                                | 2.01  | 2.01  | 784            | 0.930     |
| 5   | [1]         | NW-5        | 60.3                               | 2.00                   | 0.12                                | 4.02  | 4.02  | 900            | 1.520     |
| 6   | [1]         | NW-6        | 65.2                               | 2.00                   | 0.13                                | 4.02  | 4.02  | 1056           | 1.340     |
| 7   | [1]         | W-08        | 103.3                              | 0.67                   | 0.09                                | 5.75  | 5.75  | 1670           | 0.729     |
| 8   | [1]         | W-12        | 137.5                              | 0.67                   | 0.09                                | 5.75  | 5.75  | 1719           | 0.776     |
| 9   | [1]         | No. 1       | 65.1                               | 1.33                   | 0.13                                | 1.58  | 1.58  | 1101           | 0.710     |
| 10  | [1]         | No. 2       | 70.8                               | 1.33                   | 0.12                                | 2.75  | 2.75  | 1255           | 0.700     |
| 11  | [1]         | No. 3       | 71.8                               | 1.33                   | 0.12                                | 4.22  | 4.22  | 1379           | 0.760     |
| 12  | [1]         | No. 4       | 103.4                              | 1.33                   | 0.14                                | 4.22  | 4.22  | 1697           | 0.720     |
| 13  | [1]         | No. 5       | 76.7                               | 2.00                   | 0.11                                | 4.22  | 4.22  | 1159           | 1.000     |
| 14  | [1]         | No. 6       | 74.1                               | 1.33                   | 0.12                                | 9.31  | 9.31  | 1412           | 0.720     |
| 15  | [1]         | No. 7       | 71.5                               | 1.33                   | 0.12                                | 7.92  | 7.92  | 1499           | 0.740     |
| 16  | [1]         | No. 8       | 76.1                               | 1.33                   | 0.11                                | 11.52   | 11.52   | 1639           | 0.760     |
| 17  | [1]         | M35X        | 62.6                               | 2.00                   | 0.15                                | 6.48  | 6.48  | 1049           | 1.490     |
| 18  | [1]         | M35H        | 68.6                               | 2.00                   | 0.15                                | 6.48  | 6.48  | 1055           | 1.500     |
| 19  | [1]         | P35H        | 66.5                               | 2.00                   | 0.15                                | 6.48  | 6.48  | 959            | 1.500     |
| 20  | [1]         | M30H        | 61.4                               | 2.00                   | 0.13                                | 6.48  | 6.48  | 1020           | 1.450     |
| 21  | [1]         | MW35H       | 59.7                               | 2.00                   | 0.15                                | 6.48  | 6.48  | 1012           | 1.500     |
| 22  | [1]         | MAE03       | 58.3                               | 0.60                   | 0.03                                | 3.83  | 3.83  | 1460           | 0.623     |
| 23  | [1]         | MAE07       | 58.1                               | 0.60                   | 0.03                                | 6.42  | 6.42  | 1676           | 0.592     |
| 24  | [1]         | W48M6       | 82.3                               | 0.80                   | 0.02                                | 4.44  | 4.44  | 1516           | 0.601     |
| 25  | [1]         | W48M4       | 82.3                               | 0.80                   | 0.02                                | 4.12  | 4.12  | 1479           | 1.005     |
| 26  | [1]         | W72M8       | 82.3                               | 0.80                   | 0.02                                | 7.24  | 7.24  | 2066           | 1.014     |
| 27  | [1]         | W72M6       | 82.3                               | 0.80                   | 0.02                                | 6.65  | 6.65  | 2015           | 1.023     |
| 28  | [1]         | W72M8       | 101.8                              | 0.80                   | 0.02                                | 7.24  | 7.24  | 2128           | 1.005     |
| 29  | [1]         | W96M8       | 101.8                              | 0.80                   | 0.02                                | 9.41  | 9.41  | 2483           | 1.022     |
| 30  | [1]         | SMZ01       | 83.6                               | 0.65                   | 0.00                                | 2.10  | 2.10  | 1154           | 0.865     |
| 31  | [1]         | SMZ03       | 83.3                               | 0.65                   | 0.00                                | 2.10  | 2.10  | 2081           | 0.809     |
| 32  | [1]         | W8N18       | 72.7                               | 2.00                   | 0.15                                | 11.31   | 11.31   | 882            | 1.500     |
| 33  | [1]         | W8N13       | 79.0                               | 2.00                   | 0.10                                | 11.31   | 11.31   | 762            | 1.500     |
| 34  | [1]         | W8N8H       | 79.4                               | 2.00                   | 0.06                                | 11.31   | 11.31   | 689            | 1.500     |
| 35  | [1]         | TAK01       | 62.3                               | 1.80                   | 0.11                                | 4.78  | 4.78  | 971            | 1.500     |
| 36  | [1]         | TAK02       | 62.3                               | 1.80                   | 0.11                                | 6.91  | 6.91  | 987            | 1.500     |
| 37  | [1]         | TAK03       | 62.3                               | 1.20                   | 0.11                                | 4.78  | 4.78  | 1288           | 1.000     |
| 38  | [2]         | S-1         | 79.3                               | 1.00                   | 0.00                                | 5.45  | 2.89  | 428            | 1.607     |
| 39  | [2]         | S-2         | 65.1                               | 1.00                   | 0.07                                | 5.45  | 2.89  | 720            | 1.114     |
| 40  | [2]         | S-3         | 69.0                               | 1.00                   | 0.13                                | 5.45  | 2.89  | 851            | 0.559     |
| 41  | [2]         | S-4         | 75.2                               | 1.00                   | 0.00                                | 8.00  | 2.89  | 600            | 1.213     |
| 42  | [2]         | S-5         | 73.1                               | 1.00                   | 0.06                                | 8.00  | 2.89  | 790            | 0.784     |
| 43  | [2]         | S-6         | 70.5                               | 1.00                   | 0.13                                | 8.00  | 2.89  | 970            | 0.735     |
| 44  | [2]         | S-7         | 71.2                               | 1.00                   | 0.06                                | 5.45  | 5.45  | 800            | 0.935     |
| 45  | [2]         | S-F         | 60.5                               | 1.00                   | 0.04                                | 5.45  | 2.89  | 487            | 2.060     |
| 46  | [3]         | HW1         | 69.0                               | 1.80                   | 0.06                                | 3.50  | 3.50  | 442            | 2.386     |
| 47  | [3]         | HW2         | 69.0                               | 1.80                   | 0.03                                | 3.50  | 3.50  | 375            | 2.441     |
| 48  | [3]         | HW3         | 69.0                               | 1.80                   | 0.00                                | 3.50  | 3.50  | 234            | 2.063     |
| 49  | [3]         | HW4         | 69.0                               | 1.80                   | 0.03                                | 3.50  | 7.00  | 363            | 2.225     |
| 50  | [3]         | HW5         | 69.0                               | 1.80                   | 0.03                                | 3.50  | 1.78  | 372            | 2.908     |
| 51  | [4]         | HSCW1       | 104.0                              | 1.25                   | 0.04                                | 6.74  | 2.51  | 735            | 0.968     |
| 52  | [4]         | HSCW2       | 93.0                               | 1.25                   | 0.09                                | 6.74  | 2.51  | 845            | 1.125     |
| 53  | [4]         | HSCW3       | 86.0                               | 1.25                   | 0.09                                | 4.01  | 2.51  | 625            | 0.928     |
| 54  | [4]         | HSCW4       | 91.0                               | 1.25                   | 0.22                                | 4.01  | 2.51  | 866            | 0.763     |
| 55  | [4]         | HSCW5       | 84.0                               | 1.25                   | 0.09                                | 6.74  | 4.01  | 801            | 1.318     |
| 56  | [4]         | HSCW6       | 90.0                               | 1.25                   | 0.05                                | 6.74  | 4.01  | 745            | 1.342     |
| 57  | [4]         | HSCW7       | 102.0                              | 1.25                   | 0.08                                | 4.01  | 4.01  | 800            | 1.265     |
| 58  | [5]         | SW-1        | 90.0                               | 2.36                   | 0.15                                | 1.66  | 1.66  | 260            | 1.594     |
| 59  | [5]         | SW-2        | 90.0                               | 2.36                   | 0.15                                | 6.97  | 6.97  | 367            | 2.836     |
| 60  | [5]         | SW-3        | 60.0                               | 2.36                   | 0.15                                | 1.66  | 1.66  | 200            | 3.642     |
| 61  | [5]         | SW-4        | 90.0                               | 2.36                   | 0.25                                | 1.66  | 1.66  | 255            | 2.061     |
| 62  | [5]         | SW-5        | 90.0                               | 1.50                   | 0.15                                | 1.66  | 1.66  | 350            | 1.714     |
| 63  | [6]         | HPCW-01     | 61.4                               | 2.10                   | 0.16                                | 2.10  | 3.36  | 326            | 2.019     |
| 64  | [6]         | HPCW-02     | 73.6                               | 2.10                   | 0.14                                | 2.10  | 3.36  | 333            | 2.480     |
| 65  | [6]         | HPCW-03     | 75.3                               | 2.10                   | 0.13                                | 2.10  | 5.09  | 379            | 2.448     |
| 66  | [6]         | HPCW-04     | 86.0                               | 2.10                   | 0.12                                | 2.10  | 5.09  | 370            | 2.677     |

Table 1: Details of HSC walls reported by researchers<sup>1-6</sup>

### 3.2 AIJ

$$V_n = tL\rho_t f_{yt} \cot\phi + 0.5 \tan\theta (1 - \beta) tLv f'c \quad (2)$$

where:

$V_n$  = nominal wall shear strength (N)

$t$  = thickness of wall panel (mm)

$\cot\phi = 1.0$

$\tan\theta = \sqrt{(H/L)^2 + 1} - H/L$

$\beta = (1 + \cot^2\phi)\rho_t f_{yt} (v f'c)^{-1}$

$v = 0.7 - (f'c/2000)$

### 3.3 EC8

For diagonal compression failure of the web due to shear:

$$V_n = \alpha_{cw} t z v_1 f'c (\cot\theta + \tan\theta)^{-1} \quad (3)$$

where:

$V_n$  = nominal wall shear strength (N), which for the critical region, it may be taken as 40% of the calculated value

$\alpha_{cw}$  = coefficient taking account of the state of the stress in the compression chord, which may be taken as 1.0 for non-prestressed structures;  $[1 + P/(f'c A_g)]$  for  $0 < P/(f'c A_g) \leq 0.25$ ; 1.25 for  $0.25 < P/(f'c A_g) \leq 0.5$ ; or  $2.5 [1 - P/(f'c A_g)]$  for  $0.5 < P/(f'c A_g) < 1.0$

$t$  = thickness of wall panel (mm)

$z$  = inner lever arm, for a member with constant depth, corresponding to the bending moment in the element under consideration, which may be taken equal to  $0.8L$

$v_1$  = strength reduction factor for concrete cracked in shear, which is  $0.6 (1.0 - f'd/250)$

$\cot\theta = \tan\theta = 1.0$

For diagonal tension failure of the web due to shear:

$$\text{If } M/(VL) \geq 2.0: V_n = td [C_{Rd,c} k (100\rho_l f'c)^{1/3} + k_1 \sigma_{cp}] + z t \rho_t f_{yt} \cot\theta \quad (4)$$

$$\text{If } M/(VL) < 2.0: V_n = td [C_{Rd,c} k (100\rho_l f'c)^{1/3} + k_1 \sigma_{cp}] + 0.75 t \rho_t f_{yt} M/V \quad (5)$$

where:

$V_n$  = nominal wall shear strength (N)

$t$  = thickness of wall panel (mm)

$d$  = effective depth of a cross section (mm)

$C_{Rd,c} = 0.18/\gamma_c$ , which  $\gamma_c$  is taken as 1.0 for nominal strength without reduction factor for material

$k = 1 + \sqrt{(200/d)} \leq 2.0$

$k_1 = 0.15$

$\sigma_{cp} = P/A_g < 0.2 f'c$  (MPa)

$z = 0.8L$

$\cot\theta = \tan\theta = 1.0$

$M$  = applied bending moment in wall

$V$  = applied shear force in wall

The minimum value of  $V_n$  from diagonal compression failure and diagonal tension failure is taken as the nominal shear strength of walls according to EC8<sup>9</sup>.

## 4 ANALYSIS RESULTS

Results are presented in terms of actual wall strengths obtained from experiments normalized by nominal wall strengths, actual mode of failures versus predicted mode of failures, and average shear stresses (shear force divided by wall web area,  $A_c$ ) normalized by square root of concrete strength. These values are then plotted against various parameters such as shear span ratio, drift ratio, axial load ratio, longitudinal and transverse reinforcement ratios, and concrete strength to investigate further the relationship between these values and those parameters. The analysis results are presented in Tables 2 and 3 as well as Figures 1 to 6.

| No. | Specimen ID | Actual Mode of Failure | Vexp / Vcal |                |      |                |      |                | Vexp / ( $A_c \sqrt{f'_c}$ ) |
|-----|-------------|------------------------|-------------|----------------|------|----------------|------|----------------|------------------------------|
|     |             |                        | ACI 318     | Predicted Mode | AIJ  | Predicted Mode | EC 8 | Predicted Mode |                              |
| 1   | NW-1        | FLEXURE                | 1.16        | FLEXURE        | 1.16 | FLEXURE        | 1.17 | SHEAR          | 0.83                         |
| 2   | NW-2        | FLEXURE                | 1.39        | SHEAR          | 1.07 | FLEXURE        | 1.58 | SHEAR          | 1.12                         |
| 3   | NW-3        | FLEXURE                | 1.48        | SHEAR          | 0.95 | FLEXURE        | 1.23 | SHEAR          | 0.71                         |
| 4   | NW-4        | FLEXURE                | 1.63        | SHEAR          | 0.91 | SHEAR          | 1.30 | SHEAR          | 0.78                         |
| 5   | NW-5        | FLEXURE                | 1.18        | SHEAR          | 0.97 | FLEXURE        | 1.22 | SHEAR          | 0.85                         |
| 6   | NW-6        | FLEXURE                | 1.36        | SHEAR          | 0.97 | FLEXURE        | 1.35 | SHEAR          | 0.96                         |
| 7   | W-08        | SHEAR                  | 1.48        | SHEAR          | 0.61 | FLEXURE        | 2.58 | SHEAR          | 1.21                         |
| 8   | W-12        | SHEAR                  | 1.46        | SHEAR          | 0.54 | FLEXURE        | 2.40 | SHEAR          | 1.08                         |
| 9   | No. 1       | SHEAR                  | 2.25        | SHEAR          | 0.90 | SHEAR          | 2.58 | SHEAR          | 1.00                         |
| 10  | No. 2       | SHEAR                  | 1.90        | SHEAR          | 0.89 | SHEAR          | 2.15 | SHEAR          | 1.10                         |
| 11  | No. 3       | SHEAR                  | 1.60        | SHEAR          | 0.89 | SHEAR          | 1.78 | SHEAR          | 1.20                         |
| 12  | No. 4       | SHEAR                  | 1.84        | SHEAR          | 0.83 | SHEAR          | 1.89 | SHEAR          | 1.23                         |
| 13  | No. 5       | SHEAR                  | 1.41        | SHEAR          | 0.87 | SHEAR          | 1.36 | SHEAR          | 0.97                         |
| 14  | No. 6       | SHEAR                  | 1.45        | SHEAR          | 0.70 | SHEAR          | 1.69 | SHEAR          | 1.21                         |
| 15  | No. 7       | SHEAR                  | 1.57        | SHEAR          | 0.80 | SHEAR          | 1.82 | SHEAR          | 1.30                         |
| 16  | No. 8       | SHEAR                  | 1.66        | SHEAR          | 0.73 | SHEAR          | 1.93 | SHEAR          | 1.38                         |
| 17  | M35X        | FLEXURE                | 1.17        | SHEAR          | 1.08 | FLEXURE        | 1.35 | SHEAR          | 0.97                         |
| 18  | M35H        | FLEXURE                | 1.13        | SHEAR          | 1.04 | FLEXURE        | 1.28 | SHEAR          | 0.94                         |
| 19  | P35H        | FLEXURE                | 1.04        | SHEAR          | 0.96 | FLEXURE        | 1.18 | SHEAR          | 0.86                         |
| 20  | M30H        | FLEXURE                | 1.15        | SHEAR          | 1.13 | FLEXURE        | 1.35 | SHEAR          | 0.96                         |
| 21  | MW35H       | FLEXURE                | 1.16        | SHEAR          | 1.07 | FLEXURE        | 1.34 | SHEAR          | 0.96                         |
| 22  | MAE03       | SHEAR                  | 1.46        | SHEAR          | 0.64 | SHEAR          | 3.00 | SHEAR          | 1.10                         |
| 23  | MAE07       | SHEAR                  | 1.52        | SHEAR          | 0.68 | SHEAR          | 2.38 | SHEAR          | 1.26                         |
| 24  | W48M6       | SHEAR                  | 1.10        | SHEAR          | 0.98 | FLEXURE        | 1.98 | SHEAR          | 0.81                         |
| 25  | W48M4       | SHEAR                  | 1.12        | SHEAR          | 1.05 | FLEXURE        | 1.96 | SHEAR          | 0.79                         |
| 26  | W72M8       | SHEAR                  | 1.33        | SHEAR          | 0.98 | FLEXURE        | 1.88 | SHEAR          | 1.10                         |
| 27  | W72M6       | SHEAR                  | 1.30        | SHEAR          | 1.01 | FLEXURE        | 1.92 | SHEAR          | 1.08                         |
| 28  | W72M8       | SHEAR                  | 1.23        | SHEAR          | 1.01 | FLEXURE        | 1.91 | SHEAR          | 1.02                         |
| 29  | W96M8       | SHEAR                  | 1.44        | SHEAR          | 0.95 | FLEXURE        | 1.80 | SHEAR          | 1.19                         |
| 30  | SMZ01       | FLEXURE                | 1.30        | SHEAR          | 1.00 | FLEXURE        | 3.31 | SHEAR          | 0.62                         |
| 31  | SMZ03       | FLEXURE                | 2.35        | SHEAR          | 0.90 | FLEXURE        | 5.96 | SHEAR          | 1.13                         |
| 32  | W8N18       | FLEXURE                | 1.11        | SHEAR          | 1.06 | FLEXURE        | 1.29 | SHEAR          | 0.92                         |
| 33  | W8N13       | FLEXURE                | 1.07        | FLEXURE        | 1.07 | FLEXURE        | 1.11 | SHEAR          | 0.77                         |
| 34  | W8N8H       | FLEXURE                | 1.03        | FLEXURE        | 1.03 | FLEXURE        | 1.04 | SHEAR          | 0.69                         |
| 35  | TAK01       | FLEXURE                | 1.11        | FLEXURE        | 1.11 | FLEXURE        | 1.11 | FLEXURE        | 0.76                         |
| 36  | TAK02       | FLEXURE                | 1.04        | FLEXURE        | 1.04 | FLEXURE        | 1.10 | SHEAR          | 0.77                         |
| 37  | TAK03       | FLEXURE                | 1.22        | SHEAR          | 0.99 | FLEXURE        | 1.43 | SHEAR          | 1.01                         |
| 38  | S-1         | SHEAR                  | 1.11        | SHEAR          | 0.89 | FLEXURE        | 1.22 | SHEAR          | 0.64                         |
| 39  | S-2         | SHEAR                  | 1.96        | SHEAR          | 0.90 | SHEAR          | 1.25 | SHEAR          | 1.19                         |
| 40  | S-3         | SHEAR                  | 2.28        | SHEAR          | 1.01 | SHEAR          | 0.98 | SHEAR          | 1.37                         |
| 41  | S-4         | SHEAR                  | 1.58        | SHEAR          | 0.84 | FLEXURE        | 1.21 | SHEAR          | 0.92                         |
| 42  | S-5         | SHEAR                  | 2.10        | SHEAR          | 0.90 | SHEAR          | 1.24 | SHEAR          | 1.23                         |
| 43  | S-6         | SHEAR                  | 2.59        | SHEAR          | 1.13 | SHEAR          | 1.76 | SHEAR          | 1.54                         |
| 44  | S-7         | SHEAR                  | 1.52        | SHEAR          | 0.91 | FLEXURE        | 2.52 | SHEAR          | 1.26                         |
| 45  | S-F         | FLEXURE                | 1.34        | SHEAR          | 1.20 | FLEXURE        | 2.53 | SHEAR          | 0.83                         |
| 46  | HW1         | FLEXURE                | 1.22        | FLEXURE        | 1.22 | FLEXURE        | 2.37 | FLEXURE        | 0.52                         |
| 47  | HW2         | FLEXURE                | 1.25        | FLEXURE        | 1.25 | FLEXURE        | 2.63 | FLEXURE        | 0.44                         |
| 48  | HW3         | FLEXURE                | 0.98        | FLEXURE        | 0.98 | FLEXURE        | 2.78 | FLEXURE        | 0.28                         |
| 49  | HW4         | FLEXURE                | 1.21        | FLEXURE        | 1.21 | FLEXURE        | 1.85 | FLEXURE        | 0.43                         |
| 50  | HW5         | FLEXURE                | 1.24        | FLEXURE        | 1.24 | FLEXURE        | 1.87 | FLEXURE        | 0.44                         |
| 51  | HSCW1       | SHEAR                  | 2.20        | SHEAR          | 0.83 | SHEAR          | 2.60 | SHEAR          | 1.09                         |
| 52  | HSCW2       | SHEAR                  | 2.60        | SHEAR          | 1.04 | SHEAR          | 2.70 | SHEAR          | 1.33                         |
| 53  | HSCW3       | SHEAR                  | 1.96        | SHEAR          | 0.82 | SHEAR          | 2.10 | SHEAR          | 1.02                         |
| 54  | HSCW4       | SHEAR                  | 2.68        | SHEAR          | 1.09 | SHEAR          | 2.19 | SHEAR          | 1.38                         |
| 55  | HSCW5       | SHEAR                  | 1.93        | SHEAR          | 0.99 | SHEAR          | 1.99 | SHEAR          | 1.32                         |
| 56  | HSCW6       | SHEAR                  | 1.77        | SHEAR          | 0.87 | SHEAR          | 2.00 | SHEAR          | 1.19                         |
| 57  | HSCW7       | SHEAR                  | 1.85        | SHEAR          | 0.85 | SHEAR          | 2.03 | SHEAR          | 1.20                         |
| 58  | SW-1        | FLEXURE                | 1.13        | SHEAR          | 1.10 | FLEXURE        | 0.98 | FLEXURE        | 0.39                         |
| 59  | SW-2        | FLEXURE                | 0.95        | FLEXURE        | 0.95 | FLEXURE        | 1.00 | FLEXURE        | 0.55                         |
| 60  | SW-3        | FLEXURE                | 1.10        | FLEXURE        | 1.10 | FLEXURE        | 0.99 | FLEXURE        | 0.37                         |
| 61  | SW-4        | FLEXURE                | 1.11        | SHEAR          | 0.73 | FLEXURE        | 1.03 | SHEAR          | 0.38                         |
| 62  | SW-5        | SHEAR                  | 1.24        | SHEAR          | 0.94 | FLEXURE        | 1.10 | SHEAR          | 0.53                         |
| 63  | HPCW-01     | FLEXURE                | 0.98        | FLEXURE        | 0.98 | FLEXURE        | 0.95 | FLEXURE        | 0.42                         |
| 64  | HPCW-02     | FLEXURE                | 1.00        | FLEXURE        | 1.00 | FLEXURE        | 1.10 | FLEXURE        | 0.39                         |
| 65  | HPCW-03     | FLEXURE                | 0.99        | FLEXURE        | 0.99 | FLEXURE        | 0.74 | FLEXURE        | 0.44                         |
| 66  | HPCW-04     | FLEXURE                | 1.03        | FLEXURE        | 1.03 | FLEXURE        | 1.09 | FLEXURE        | 0.40                         |

Table 2: Values of normalized actual wall strengths and normalized average shear stresses; actual mode of failure and predicted mode of failure

| Statistical Parameters | V <sub>exp</sub> / V <sub>cal</sub> |      |      | V <sub>exp</sub> / (A <sub>c</sub> f <sub>o</sub> ) |
|------------------------|-------------------------------------|------|------|---|
|                        | ACI 318                             | AIJ  | EC 8 |   |
| Minimum Value          | 0.95                                | 0.54 | 0.74 | 0.28  |
| Maximum Value          | 2.68                                | 1.25 | 5.96 | 1.54  |
| Average (Mean Value)   | 1.46                                | 0.96 | 1.77 | 0.91  |
| Standard Deviation     | 0.44                                | 0.15 | 0.80 | 0.32  |
| Covariance             | 0.30                                | 0.16 | 0.45 | 0.35  |

Table 3: Statistical parameters of normalized actual wall strengths and normalized average shear stresses

As observed, in general, the ACI and EC8 methods underestimate the actual wall strengths. It is understood that most of building codes tend to give lower predictions on strengths such that the design formulas are safe enough to be used for practical design. The AIJ method seems to be the most accurate, with the lowest coefficient of variation compared to the other methods. However, the AIJ method may overestimate wall strengths in some cases.

Comparing the actual mode of failure versus predicted mode of failure, the AIJ method gives the least false predictions of modes of failure among the three codes. The AIJ method fails to predict modes of failure of 13 specimens out of 66 specimens whereas the ACI-318 method fails in 17 specimens and the EC8 method fails in 20 specimens. Further investigation on the failure modes shows that most of the time, the AIJ method gives nominal wall shear strengths higher than the actual ones, which results in the tendency of predicting flexural failures instead of shear failures. On the other hand, the ACI-318 and the EC8 methods tend to give lower nominal wall shear strengths compared to the actual ones, and hence resulting in the tendency of predicting shear failures instead of flexural failures.

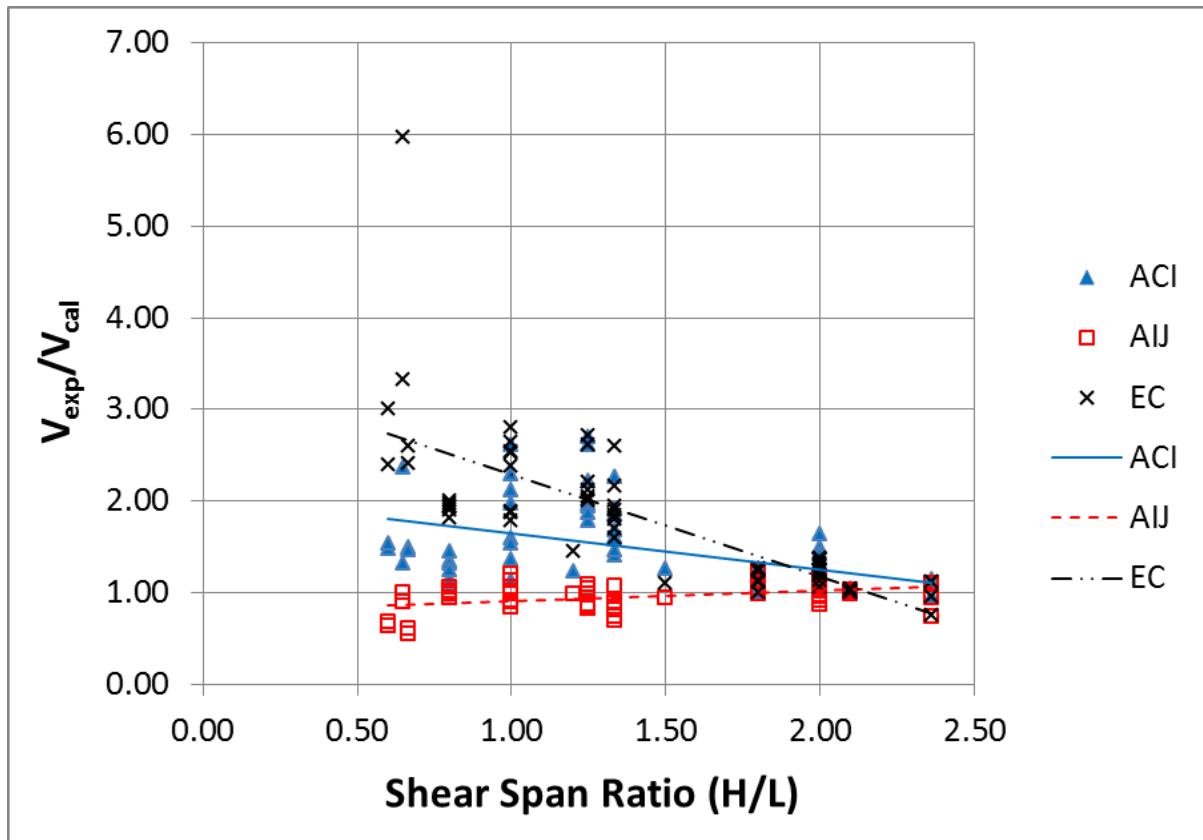


Figure 1: Normalized actual wall strengths plotted against shear span ratio

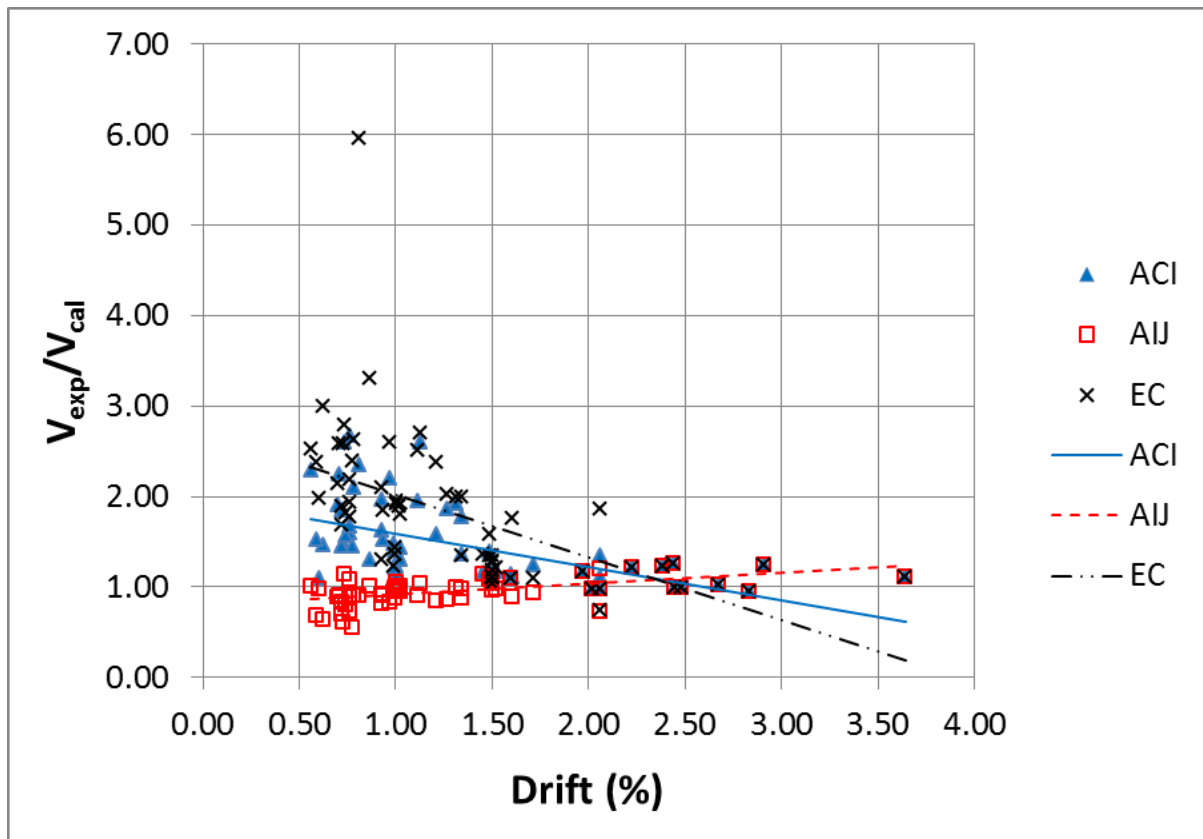


Figure 2: Normalized actual wall strengths plotted against drift ratio

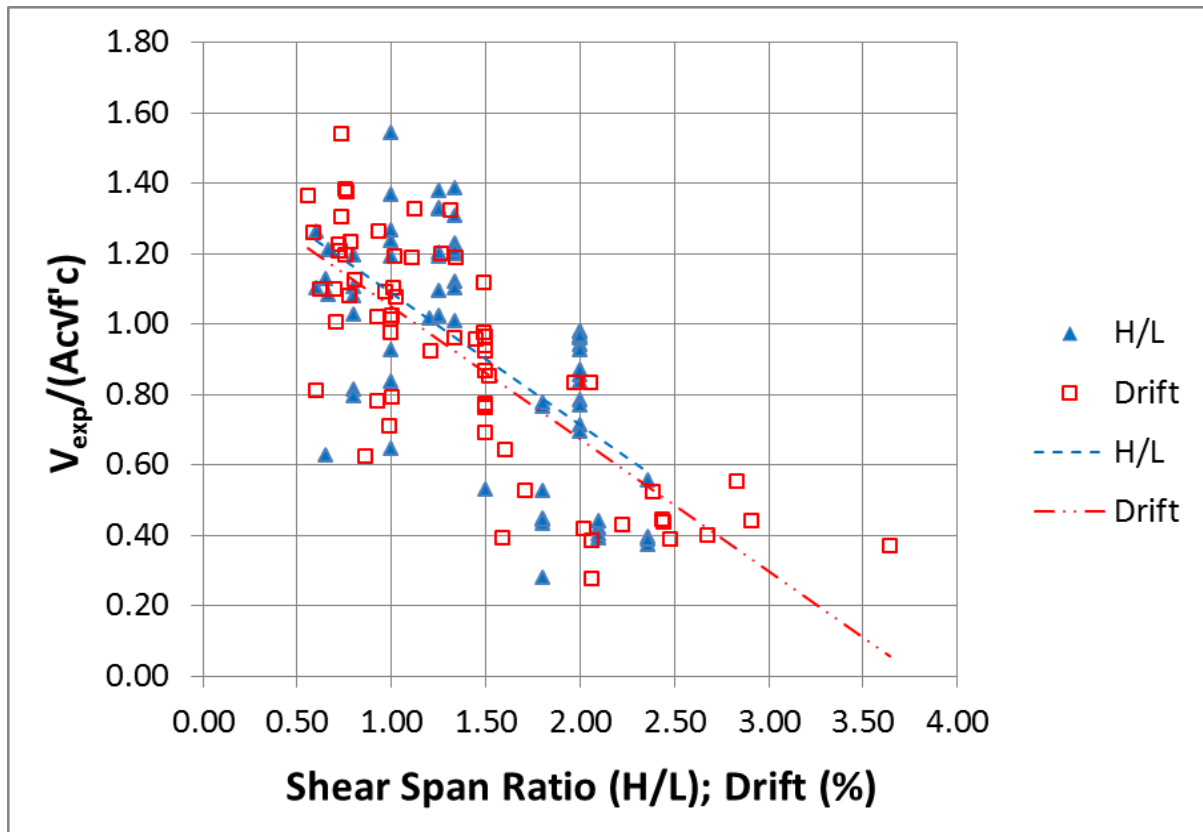


Figure 3: Normalized average shear stresses plotted against shear span ratio and drift ratio

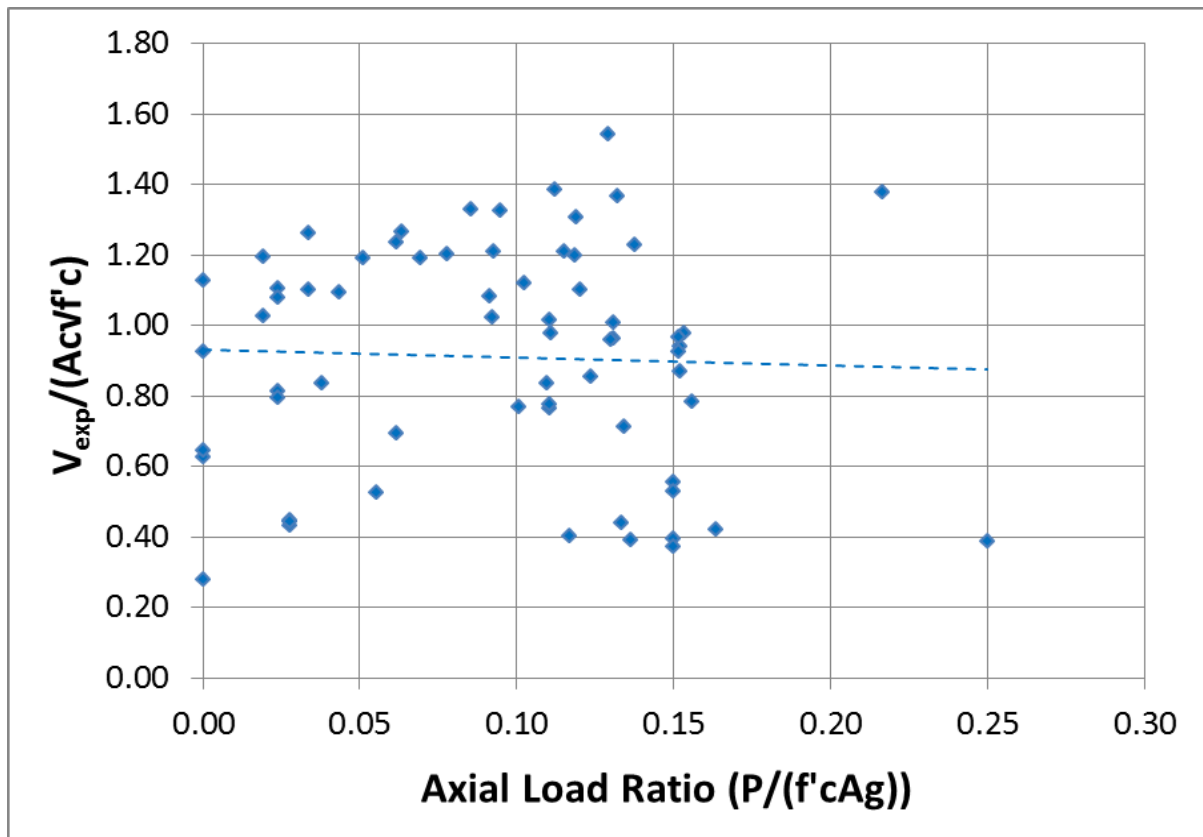


Figure 4: Normalized average shear stresses plotted against axial load ratio

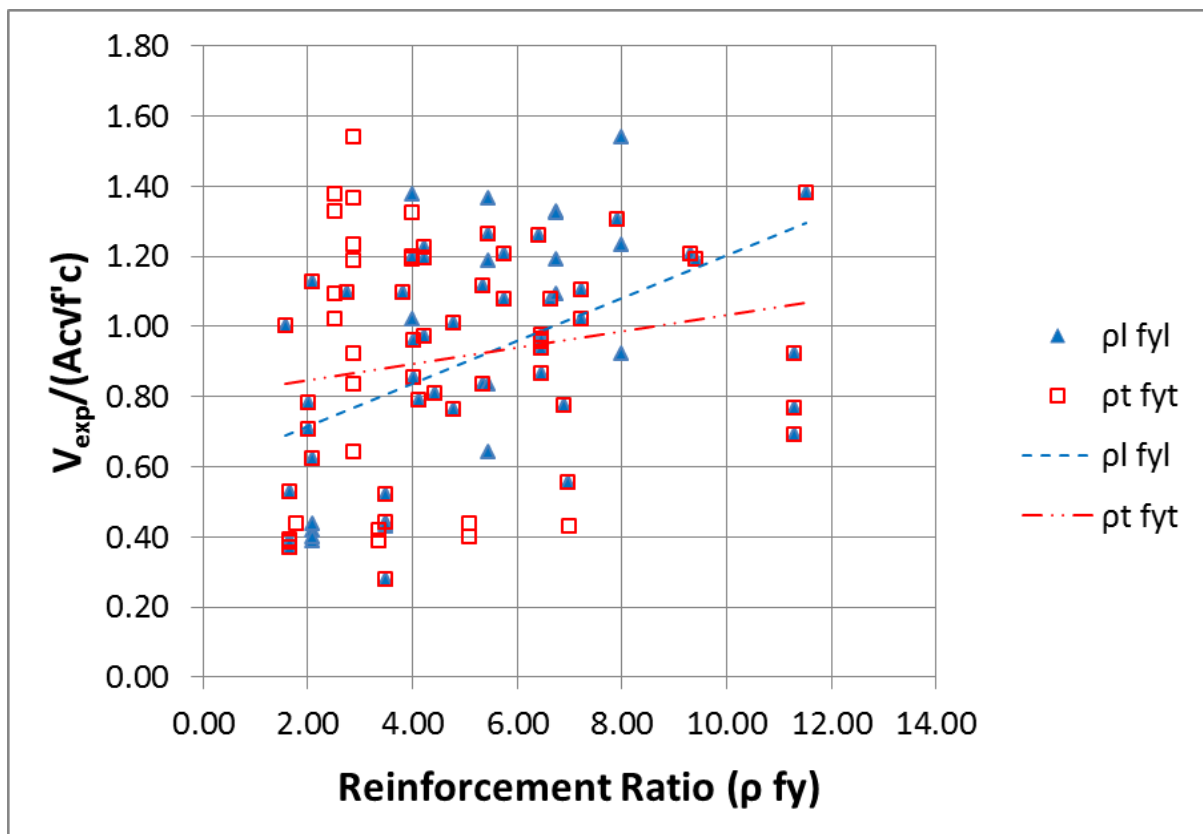


Figure 5: Normalized average shear stresses plotted against reinforcement ratio



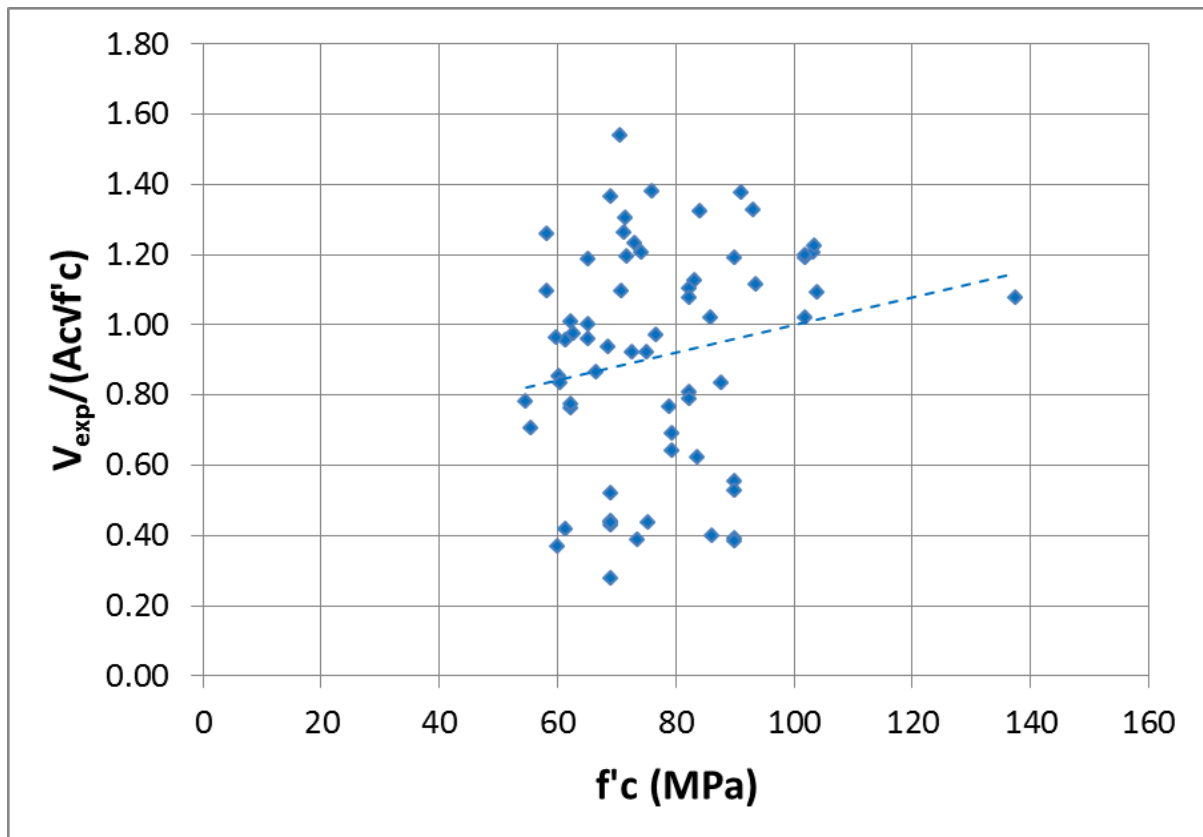


Figure 6: Normalized average shear stresses plotted against concrete strength

From Figure 1, it can be concluded that both the ACI and EC8 formulas underestimate the wall strengths in low shear span ratios (i.e., shear behavior dominates) whereas in high shear span ratios (i.e., flexural behavior dominates), they predict relatively close to the actual wall strengths. Similar phenomenon can also be observed (Figure 2) from the drift ratio, which shows that both the ACI and EC8 formulas underestimate the strength of walls failing in low drift ratio (i.e., shear failure) whereas they predict more accurately the strength of walls failing in high drift ratio (i.e., flexural failure). This means that for the flexural strength, the flexural theories given in those building codes are quite reasonable for predicting the actual flexural strength of HSC walls. For the shear strength, those building code formulas, which are mostly empirical, do not give accurate prediction of the actual shear strength of HSC walls. Moreover, from Figure 3, another conclusion that can be drawn is that as the shear span ratio and the drift ratio increase, the normalized average shear stresses tend to reduce. This means that the flexural behavior is more dominant in high shear span ratio and high drift ratio. Furthermore, according to Figure 4, it seems that an axial load of up to  $0.15 (f'_c A_g)$  does not affect much the wall strengths. The trend line of normalized average shear stresses is nearly flat regardless of the changes in the axial load ratio.

Figure 5 shows that the longitudinal reinforcement affects wall strengths more than the transverse reinforcement. The normalized average shear stresses (i.e., wall strengths) increase more when the longitudinal reinforcement ratio increases, as compared to the increment due to the increase in the transverse reinforcement ratio. This phenomenon, however, is not taken into account in most building code formulas for calculating wall shear strengths. Most of building code formulas only take into account the contribution of the transverse reinforcement while neglecting the contribution of the longitudinal reinforcement. Thus, there is a need to develop a general expression to take into account the contribution of the longitudinal reinforcement when calculating wall shear strengths in order to obtain better predictions. Furthermore, from further investigation of the data, in some cases the ACI-318 and EC8 methods underestimate wall shear strengths because of the upper limit that is imposed on the maximum wall shear strength. For example, in ACI-318, there is a limitation on the value of the maximum shear stress in walls, which is set at  $0.83\sqrt{f'_c}$ . From the analysis results, it is shown that the average shear stresses in HSC walls is about  $0.91\sqrt{f'_c}$  which exceeds the maximum limit provided by ACI-318. Hence, the ACI-318 method can underestimate wall shear strengths because of the upper

bound values of the nominal wall shear strength.

The effect of concrete strength is shown in Figure 6. It can be seen that the normalized average shear stresses seems to increase with an increase in concrete strength. Note, however, that the shear strength of walls also depends on factors, such as reinforcement ratios, shear span ratio, etc.

## 5 CONCLUSIONS

An analytical study on the behavior of HSC walls (above 60 MPa) based on various available experimental results is presented in this paper. Several general conclusions can be drawn. These conclusions are as follows.

Most of building code formulas underestimate the strength of HSC walls failing in shear while they can predict relatively accurately for the ones failing in flexure. The underestimation of the shear strength of HSC walls can be caused by a few inaccuracies in the shear strength formulas, but two factors are especially important. One is the neglected contribution of longitudinal reinforcement to wall shear strengths, and another one is the limitation on the maximum shear strength values, which seems to be quite conservative for HSC walls.

This paper discusses 66 HSC wall specimens that the authors can find in the literature. More experimental studies on the behavior of HSC walls (above 60 MPa), especially those failing in shear, are needed to provide more data which can be used to develop a general expression for predicting the strength of HSC walls. That kind of research is currently being done by the authors.

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